Coulomb Excitation Paths of High-K Isomer Bands in ^{178}Hf

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Three distinctly different mechanisms are shown to populate the $K^\pi = 6^+$ ($t_{1/2} = 77$ ns), 16^+ (31 yr), and 8^- (4 s) isomer bands of ^{178}Hf by Coulomb excitation. High spin states of the three isomer bands were populated by Coulomb excitation of a hafnium target with a 650 MeV ^{136}Xe beam. Although direct population of high-K bands is highly K-forbidden, isomer bands in ^{178}Hf were populated up to spins $13^+_{K=6}$, $20^+_{K=16}$, and $14^-_{K=8}$ with in-band γ yields of $\sim 10^{-4}$ of the ground state band. The data are consistent with a rapid increase in K mixing with increasing spin in the isomer bands.

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The projection K of the total angular momentum I on the symmetry axis of a deformed nucleus appears to be conserved, as evidenced by the existence of "K isomers," nuclear states that are metastable despite the availability of allowed decay paths. In nuclei that exhibit axial symmetry, K is expected to be a good quantum number, so that an electromagnetic (EM) transition between two basis states $|I_i M_i K_i\rangle$ and $|I_f M_f K_f\rangle$ must obey the selection rule $|\Delta K| \leq \lambda$, where $\Delta K \equiv K_f - K_i$, and λ is the order of the electromagnetic transition [1]. However, K-forbidden γ decays are known to be merely hindered, rather than truly forbidden [2], suggesting that K is not always a good quantum number. The degree of hindrance generally increases with the forbiddenness of an EM transition, $n \equiv |\Delta K| - \lambda$.

Rotational bands of high K are not expected to be populated by Coulomb excitation from the ground state band (GSB), since the high-multipolarity transitions required by the K-selection rule have a negligible transition probability. Nonetheless, Coulomb excitation of high-K bands has been observed, in apparent violation of the K selection rule, but the mechanism has remained a mystery for years. Coriolis mixing or the breaking of axial symmetry can result in EM transitions, such as direct excitation of a high-K isomer band from the GSB, that are forbidden between pure-K bands. Alternatively, if there is a multistep path available, consisting of successive allowed or low-forbiddenness transitions, then multiple Coulomb excitations can populate high-K bands. Significant population of an isomer can be achieved if the stronger low-n transitions can overcome the less effective population via multistep excitation.

Coulomb excitation of the $K^\pi = 8^-$ isomer was first reported by Hamilton *et al.* in 1982 [3] and confirmed by Xie *et al.* in 1993 [4], but observation of the isomer decay alone has proven insufficient to determine the population mechanism. The present experiment has studied prompt γ-ray yields of high spin states in the isomer bands to elucidate the population paths of high-K bands in ^{178}Hf. A beam of 650 MeV ^{136}Xe, provided by the ATLAS linear accelerator at Argonne National Laboratory, was used to Coulomb excite a 0.51 mg/cm^2, 89% enriched ^{178}Hf target. Gammasphere recorded the γ rays in coincidence with Rochester's highly segmented 4π parallel plate avalanche counter (PPAC) array, CHICO [5], which recorded the particle kinematics. CHICO is capable of a mass resolution of $\frac{\Delta m}{m} \approx 5\%$, enabling the identification of the targetlike and projectilelike particles. Event-by-event Doppler-shift corrections improved the γ-ray energy resolution to $\approx 0.5\%$.

The γ-ray yields of several rotational bands in ^{178}Hf were measured relative to the $I^\pi_K = 8^+_0 \rightarrow 6^+_0$ transition for six 9°-wide intervals in the range $25° < \theta^{\rm scat}_{\rm lab} < 80°$. Prompt γ yields were measured using a γ-γ-γ cube for the GS, 4^+, 8^-, and 16^+ bands, a single-γ spectrum for the 2^+ band, and a prompt-delayed matrix gated on the isomer decays for the 6^+ band. The tentative 20^+ level added to the GSB by Mullins *et al.* [6] has been confirmed, and the γ band [7,8], the 4^+ band [7,9], and the 6^+ band [6] have been extended to higher spin (Fig. 1).

Using a 50 ns $< t <$ 500 ns time window for the delayed γ rays, the decay branches of the 77 ns, $K^\pi = 6^+$ isomer were clearly observed between beam pulses. Four known decay paths were observed directly, to the

$I_K^\pi = 4_0^+$, 6_0^+, 4_2^+, and 8_8^- levels. In addition, the known, highly converted 40 keV branch to the $K = 4^+$ band head [10] was observed indirectly by the secondary 1207 keV decay to the GSB (Fig. 1). The width of this branch, 19(1)% of the total decay width, was measured here for the first time and proves important in explaining the population of the 6^+ isomer band.

The software GOSIA [11] was used to calculate expected γ-ray yields from pure Coulomb excitation and to fit matrix elements to the experimental yields by a χ^2 minimization. The errors quoted herein represent correlated errors that gave an increase of 1 in the total χ^2. In most cases, only yields for "safe angles" of $\theta_{\mathrm{lab}}^{\mathrm{scat}} < 53°$ (separation between the nuclear surfaces ≥ 5 fm [12]) were included in the fits.

The sets of reduced matrix elements $\langle K_f I_f \| \mathcal{M}\lambda \| K_i I_i \rangle$ used in the analysis were calculated using the Alaga rule for K-allowed transitions [1], whereas for K-forbidden transitions, two models were tested: A spin-dependent K-mixing (SDM) model was used, Eq. 4-95 in Bohr and Mottelson [1]. The second model assumes that one of the bands has a K component such that $|\Delta K| \leq \lambda$, and then the Alaga rule may be applied. In-band $M1$ matrix elements were calculated from branching ratios, mixing ratios, and magnetic moments.

The GS, γ, and $K^\pi = 4^+$ bands.—Iterative fits for intrinsic matrix elements connecting the GSB, γ band, and $K^\pi = 4^+$ band were calculated by first fitting the intraband $E2$ matrix elements to the relative GSB yields and then fitting to each band's yields in succession. Adjusted individually, GSB matrix elements deviated by $\leq 1.5\%$ from the rigid-rotor model. Linking the in-band matrix elements with a single quadrupole moment yielded $\sqrt{5/16\pi} e Q_o = 2.164(10)e$ b, $2.21(8)e$ b, and $2.07(10)e$ b, for the GS, γ, and 4^+ bands, respectively, consistent with a single intrinsic moment and in agreement with previous work [13]. The $B(E2; 2_2^+ \rightarrow 0_0^+)$, previously measured as 3.9(1) W.u. [14] and 3.4(3) W.u. [15], was found to be 4.0(3) W.u. from the fit of the intrinsic matrix element $\langle K = 2^+ | E2 | K = 0^+ \rangle = 0.252(11)e$ b. The $B(E2; 4_4^+ \rightarrow 2_0^+)$ was found to be $2.2(2) \times 10^{-3}$ W.u., compared to the upper limit of 0.58 W.u. from previous work [16]. The ratio of the intrinsic $E2$ matrix elements connecting the γ and 4^+ bands is $\langle K = 4^+ | E2 | K = 2^+ \rangle / \langle K = 2^+ | E2 | K = 0^+ \rangle = 1.77(11)$, which exceeds the value of $\sqrt{2}$ expected for pure one- and two-phonon γ-vibrational bands [17].

Although the GSB, γ, and 4^+ bands are not completely decoupled, calculations showed that excitation of the isomer bands could be treated as small perturbations on the 0^+, 2^+, and 4^+ band yields. The fits for these low-K bands gave reasonable agreement with the data, so that their influence on the population of the isomer bands could be tested.

The $K^\pi = 6^+$ band.—The contribution to the 6^+ isomer band population by Coulomb excitation through the 4^+ band has been determined using the Alaga rule and our measurement of $B(E2; 6_6^+ \rightarrow 4_4^+) = 1.16(6) \times 10^{-4}$ W.u., giving the intrinsic matrix element $\langle K^\pi = 6^+ | E2 | K^\pi = 4^+ \rangle = 0.094(3)e$ b. Assuming spin-dependent mixing, the contributions via direct population from the GSB and γ band also have been determined. It is

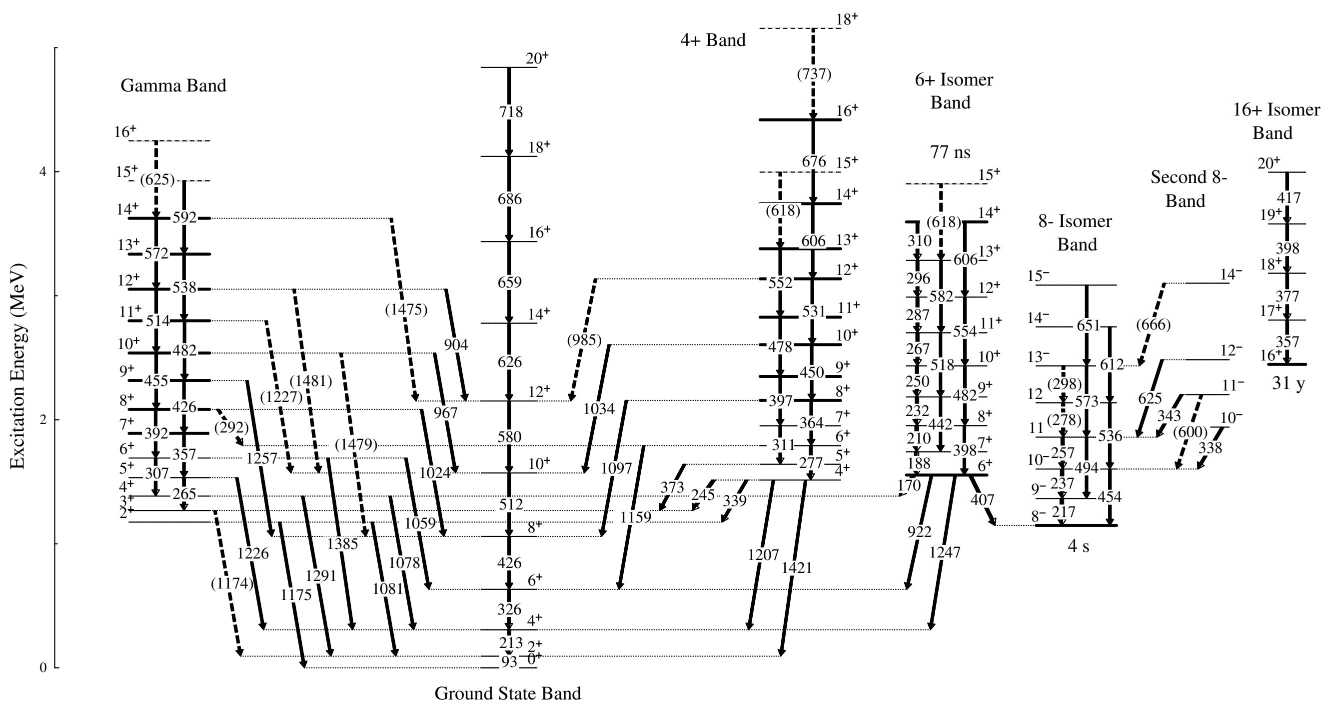

FIG. 1. A partial level diagram for ^{178}Hf. New levels and isomer levels are shown in bold. Half-lives are given for the three isomers.

clear from the $8^+ \to 6^+$ yields in Fig. 2 that destructive interference involving the $K = 6^+$, 4^+, and 2^+ bands would give insufficient yield by about 1 order of magnitude. The calculated yields from higher-spin levels show some disagreement with the data, but this is to be expected because of the explosive behavior, at high spin, of the SDM matrix elements. Still, the agreement is good for forward angles in all cases. The GSB $\to K^\pi = 2^+ \to K^\pi = 6^+$ path and the predominantly three-step GSB $\to K^\pi = 2^+ \to K^\pi = 4^+ \to K^\pi = 6^+$ path contribute about equally to the total 6^+ band population, whereas direct excitation from the GSB is significant only for $\theta_{\rm lab}^{\rm scat} > 60°$, where it makes the greatest contribution. Population via γ decay into the 6^+ band is negligible.

The $K^\pi = 8^-$ band.—The 8^- band must be treated differently, because this isomer decays by a single $E1$ transition, whereas the excitation must be dominated by $E3$ transitions. (Calculations show that reasonable $E1$ and $E5$ strengths cannot excite the 8^- band to the measured strength.) Each candidate for a population path was evaluated through a fit of an intrinsic $E3$ matrix element to the data. The 8^- band cannot be populated to the measured strengths from either the 6^+ or 4^+ band, even with unrealistically large values of the interband matrix elements. Unreasonably large values of $B(E3; K = 2^+ \to 8^-) \sim 100$ W.u. give rough agreement between the measured and calculated 8^- band yields, but this is not

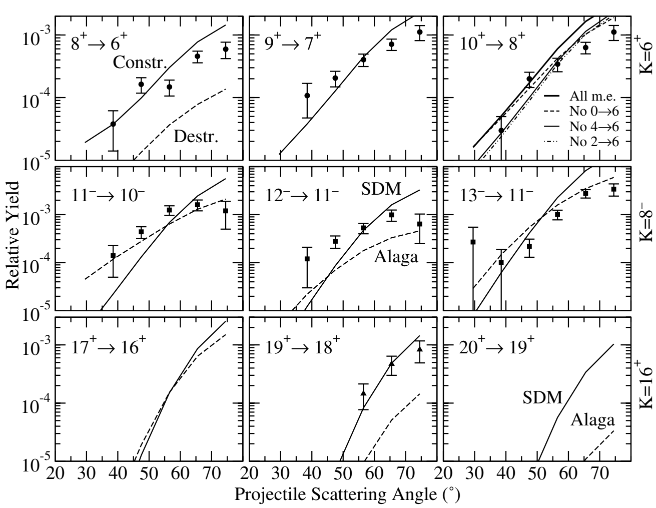

FIG. 2. Examples of measured yields (points) and calculated yields (lines) for the three isomer bands. $K = 6^+$: lines show the yields calculated from measured intrinsic matrix elements. The solid (dashed) line for the $8^+ \to 6^+$ yields represents constructive (destructive) interference involving the $K = 6^+$, 4^+, and 2^+ bands. For the $10^+ \to 8^+$ yields, the effect of removing each of the three excitation paths ($K = 0^+ \to K = 6^+$, $K = 2^+ \to K = 6^+$, and $K = 4^+ \to K = 6^+$) is compared to the total yield from all matrix elements. $K = 8^-$ and $K = 16^+$: the solid (dashed) line represents a one-parameter fit using spin-dependent mixing (a single K admixture). For the $K = 8^-$ band, the $K = 0^-$ admixture fit predicts strong odd/even population staggering.

realistic for noncollective transitions from a vibrational band to a two-quasi-particle band.

No other bands are populated to a strength comparable to that of the γ band, so the only remaining candidate for populating the 8^- band is the GSB. In the first GSB $\to 8^-$ band fit, the $\langle K^\pi = 8^- | E3 | K^\pi = 0^+ \rangle$ intrinsic matrix element was fit to the data, using the spin-dependent mixing model, but fixing two matrix elements at upper limits of $\langle 8_8^- || E3 || 6_0^+ \rangle = 9.3 \times 10^{-6} e$ b$^{3/2}$ and $\langle 8_8^- || E3 || 8_0^+ \rangle = 2.0 \times 10^{-3} e$ b$^{3/2}$, derived from branching ratios of the isomer decay [18] and the known half-life of the isomer, 4.0(2) s [13]. A fit gave good agreement with the data (Fig. 2), with $B(E3; 6_0^+ \to 9_8^-) = 0.11$ W.u. The most effective excitation paths populate the $K^\pi = 8^-$ band through the 11^-, 12^-, and 13^- levels, where $B(E3; K^\pi = 0^+ \to 8^-)$ ranges from 1.5 to 89 W.u. for the dominant transitions. Fortunately, at the top of the 8^- band, the weak population of the higher-spin states suppresses the effect of the unrealistically large matrix elements predicted by SDM. In this scenario, γ-decay feeding from the GSB is responsible for less than 10^{-4} of the total population of the 8^- isomer band.

The second fit tested the admixture of a $K = 0^-$ component in the 8^- band using the Alaga rule (Fig. 2), of special interest because it does not directly populate the even-spin states in the isomer band and preserves the lifetime of the isomer [4]. The fit gave $\langle K^\pi = 0^- | E3 | K^\pi = 0^+ \rangle = 0.33(4) e$ b$^{3/2}$. Our fit with $B(E3; K^\pi = 0^+ \to 8^-)$ values ranging from 10 to 22 W.u. reproduced the data almost as well as in the spin-dependent mixing calculation, but predicted population staggering between the odd- and even-spin states, in conflict with the data.

The spin-dependent mixing model is preferred for two reasons: First, transition probabilities are expected to be small near the bandhead where mixing is weak, whereas the $K = 0^-$ admixture predicts $B(E3; 6_0^+ \to 9_8^-) = 22$ W.u., which is unlikely since it is comparable to the most enhanced collective $B(E3)$ strengths seen in neighboring nuclei [19]. Second, the large population staggering that is predicted by the Alaga rule, using any K admixture, is not present in the data. The spin-dependent mixing model, although it may require higher order corrections for high-K bands, gives good agreement with the data for the $K = 4^+$ and 6^+ bands, reproduces the 8^- band data using reasonable matrix elements near the bandhead (~ 0.1 W.u.), and correctly predicts the absence of appreciable population staggering.

Previous experiments that Coulomb excited the 8^- band measured only the delayed isomer decay. The present analysis has the advantage of fitting the population pattern of prompt in-band γ-ray yields, rather than the isomer cross sections alone. Xie *et al.* [4] found the cross section for populating the isomer to be $2.7^{+1.9}_{-1.4}$ mb for ^{130}Te $\to$ ^{178}Hf at 560 MeV, whereas calculations with the present matrix elements give 10(2) mb and 15(2) mb for the $K = 0$ admixture and the spin-dependent mixing models, respectively. Good agreement is found with the work of Hamilton *et al.* [3] that used ^{136}Xe → ^{178}Hf at 594 MeV and measured the delayed component of the $8^+_{\rm GSB}$ yield as ≈ 0.9%, compared to the values from the present matrix elements that are 0.6(1)% and 0.9(1)%, respectively, in the aforementioned models. It should be noted that for both of the earlier experiments there is a significant contribution to the total cross section beyond the safe scattering angle, where Coulomb-nuclear interference may become significant.

The $K^\pi = 16^+$ band.—The observed population of the 16^+ isomer band was unexpected. The quadrupole moment of this band has been measured to be $\sqrt{5/16\pi} eQ_o =$ 2.27(3)e b [20] and 2.6(3)e b [21], consistent with the GSB moment. Matrix elements following the Alaga rule for the GSB → $16^+ E2$ path cannot populate the 16+ band sufficiently (Fig. 2) without exceeding measured upper limits on GSB → $K^\pi = 16^+$ γ-ray feeding, but spin-dependent mixing calculations were able to reproduce the yields with realistic $B(E2)$ values. Calculated yields show that γ-decay feeding from the GSB must dominate the population of the yrast 16^+ band, while direct excitation can contribute only $\sim 10^{-4}$ (low spin) to 10^{-2} (high spin) of the total population. The dominant feeding branches have energies of 1.3 to 1.7 MeV and either lie in the background of the Doppler-broadened 1.3 MeV ^{136}Xe peak or have low efficiency in the germanium detectors. This, coupled with the dearth of gates in the γ-γ-γ cube for decays to low spin levels and the lack of knowledge of the GSB above spin 20^+, obscures observation of the feeding; the predicted feeding strength is below the experimental sensitivity. The calculated in-band yield ratio $Y_{20^+ \to 19^+}/Y_{19^+ \to 18^+}$ was 0.71 for $52° < \theta^{\rm scat}_{\rm lab} < 79°$, in agreement with our measurement, 0.5(3). Only ^{136}Xe transitions were observed in coincidence with 16^+ band transitions in a Hf-Hf-Xe cube, showing that transfer reactions are not an important population mechanism.

In summary, three distinctly different mechanisms have been shown to populate the 6^+, 8^-, and 16^+ isomer bands: multiple-step excitation, direct K-forbidden excitation, and direct K-forbidden γ-decay feeding, respectively. The data for all three isomer bands are consistent with a rapid increase in K mixing with increasing spin. The yields of the 6^+ isomer band have been reproduced using measured values of the reduced transition probabilities for decays to the 0^+, 2^+, and 4^+ bands—with no adjustable parameters—showing that the 6^+ band is populated primarily by multistep allowed and K-forbidden excitations through the γ and 4^+ bands.

In contrast, the principal population path of the 8^- band appears to be direct $E3$ excitation from the GSB. Excitation occurs mainly to the intermediate spin levels ($\sim 12\hbar$) with $B(E3; K = 0^+ \to 8^-)$ values of the effective transitions of 1.5 to 89 W.u., in contrast with the upper limits of $B(E3; 8^-_8 \to 6^+_0) = 2.7 \times 10^{-9}$ W.u. and $B(E3; 8^-_8 \to 8^+_0) = 1.2 \times 10^{-4}$ W.u. on the transition strengths depopulating the isomer itself; this indicates that strong spin-dependent K mixing is required to sufficiently populate the band.

The $K^\pi = 16^+$ band, unexpectedly populated by Coulomb excitation, appears to be fed directly by γ decay from the GSB. An upper limit on the matrix element for feeding was established, bounded by the measured upper limits of feeding from the GSB and by the possibility of Coulomb-nuclear interference effects in the experimental data for this band, which lie beyond the $\theta^{\rm scat}$ region of safe Coulomb excitation. Limits on γ-decay feeding imply that feeding comes primarily from the highest levels ($\approx 20^+$) in the GSB and that, consequently, there must be a rapid increase in K mixing with increasing spin.

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